AEROSOL JET® MATERIAL DEPOSITION FOR HIGH RESOLUTION PRINTED ELECTRONIC APPLICATIONS

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Abstract

Aerosol Jet printing, is finding wide use in a number of electronic manufacturing applications. The Aerosol Jet systems deposit a wide variety of functional materials onto a wide variety of substrates without conventional masks or thin-film equipment. The process is non-contact, enabling traces to be printed over steps or curved surfaces. Printed features can be from less than 10 microns to several centimeters, with thicknesses from 10's of nanometers to 10's of microns. The Aerosol Jet process utilizes both low viscosity inks and diluted pastes for an operating range of approximately 1-1000cP. Typical materials that can be printed include nanoparticle metal suspensions, polymers and adhesives. Conductor traces can be printed using gold, silver or other nanoparticle inks. Conductors can also be formed by printing a seed layer, followed by electroless plating. Polymer thick film pastes can be printed to form embedded resistors. Polyimide and various epoxies can be printed for adhesives, overcoat dielectrics, etc. The system also supports deposition of semiconducting inks, carbon nanotubes (CNTs) and biomaterials. The Aerosol Jet process is compatible with a wide variety of substrates, including silicon, polyimide, glass, FR-4 and aluminum oxide. In principle, virtually any substrate can be used provided that the ink is compatible with the substrate. Applications for the Aerosol Jet technology include flexible displays, touchscreens, fuel cells, high efficiency solar cells, 3-dimensional interconnects, and embedded components including sensors, resistors, and antennae. Aerosol Jet has distinct functional and cost advantages over traditional methods such as screenprinting, lithography and wirebonding. The solution also compares well versus InkJet printing, especially in meeting high-volume manufacturing requirements. The Aerosol Jet process is compatible with a variety of substrates, including silicon, polyimide, glass, FR-4 and aluminum oxide. In principle, virtually any substrate can be used provided that the ink is compatible with the substrate. Applications for the Aerosol Jet technology include flexible displays, EMI shielding, solder-free electronics, high efficiency solar cells, 3-dimensional interconnects, and embedded components including sensors, resistors, and antennae.

INTRODUCTION

In recent years, a new class of manufacturing techniques has become available which offers manufacturers significant cost, time and quality benefits across a broad spectrum of industries. These new techniques are collectively known as additive manufacturing. During additive manufacturing, material is deposited layer by layer to build up structures or features. This is in contrast to traditional subtractive manufacturing methods where masking and etching processes are used to remove material to get to the final form. Features of additive manufacturing processes include direct CAD-driven, "Art-to-Part" processing which eliminates expensive tooling, masks and vertical/horizontal integration which lead to fewer overall manufacturing steps. These features combine to offer diverse benefits:

- *Better Product Designs* - Greater design and manufacturing flexibility offers the potential for revolutionary new end-products with improved performance based on novel size, geometries (including 3D Interconnects), materials and material combinations.
- *Time Compression and Increased Manufacturing Agility* - CAD driven, tool-less processes speed up product development and manufacturing, while allowing greater flexibility in mass customization.
- *Lower Costs* – This benefit arises because tooling and mask costs are eliminated. Process costs in terms of operator input, supplier chain complexity and work flows are reduced. Raw material is used more efficiently, thus reducing waste levels. Life-cycle costs are reduced by lower design development costs, increasing product quality and the ability to repair components.

This paper will introduce an additive manufacturing, direct write technique designed for the electronics industry that offers significant potential in the manufacture of 3D Interconnects: Aerosol Jet Deposition.

AEROSOL JET DEPOSITION SYSTEMS

The Aerosol Jet process was originally developed to fill a neglected middle ground in microelectronic fabrication. Current techniques create very small electronic features, for example by vapor deposition, and relatively large ones for example by screen-printing. No technology was capable of satisfactorily creating crucial micron-sized (1-100µm) production of interconnects, components, and devices. As electronic devices continue to shrink, thick-film fabricators are approaching the physical limits of stencil printing. Thin-film technology can deposit micron scale features but requires a highly skilled workforce and a major investment in new manufacturing capability for each new application. Thick- and thin film techniques are 2D processes and are not ideal for manufacturing 3D conformal electronic features needed for 3D Interconnects.

Figure 1. *Photo of the Aerosol Jet CE System*

HOW AEROSOL JET WORKS

The Aerosol Jet process uses aerodynamic focusing for the high-resolution deposition of colloidal suspensions and/or chemical precursor solutions. An aerosol stream of the deposition material is focused, deposited, and patterned onto a planar or 3D substrate. The basic system consists of two key components, Figure 2:

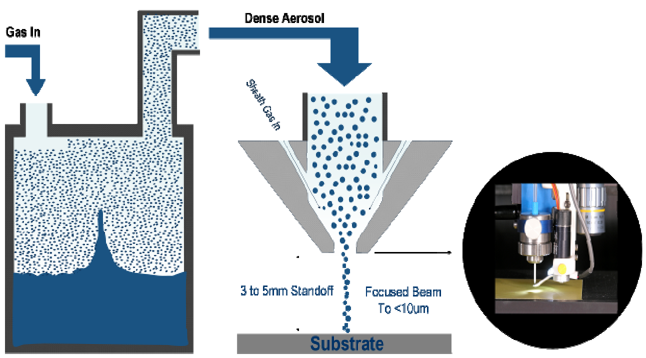

Figure 2. *Schematic of the Aerosol Jet hardware and photo of the deposition head.*

- A module for atomizing liquid raw materials (Mist Generation).
- A second module for focusing the aerosol and depositing the droplets (In-Flight Processing).

Mist Generation is accomplished using an ultrasonic or pneumatic atomizer. The aerosol stream is then focused using a flow deposition head, which forms an annular, co-axial flow between the aerosol stream and a sheath gas stream. The co-axial flow exits the print head through a nozzle directed at the substrate. The Aerosol Jet print head is capable of focusing an aerosol stream to as small as a tenth of the size of the nozzle orifice. The deposition process is CAD driven; the process directly writes the required pattern from a standard .dxf file. Patterning is accomplished by attaching the substrate to a computer-controlled platen, or by translating the flow guidance head while the substrate position remains fixed.

Thermal post processing of the deposited material is often needed to cure the material or increase properties such as electrical conductivity. Depending on the application, either conventional sintering or curing is used, or for low temperature substrate materials.

CAPABILITIES AND APPLICATIONS

Aerosol Jet printing is already being applied to a range of 2D electronics applications (Table 1), and is now being investigated for 3D Interconnect applications.

Feature sizes ~10 microns and up
Touch Screen Display Applications
Non-contact printing
Embedded and Integrated Passives
Fine line Photovoltaics (>20% efficiencies)
Thin Layer Deposits
Display Modules
Conformal Printing
3D Conformal Packaging
Sensors (internal or embedded)
Antennae

Table 1. *Aerosol Jet Application Areas*

To further leverage the process for a wide range of 3D Interconnect applications the following key capabilities can be utilized:

- 3D Structuring Capability
- Low Temperature Processing
- High Quality Deposits
- Wide Range of Materials & Substrate Combinations
- Environmental Aspects
- Competitive Cost Basis

This section of the paper will investigate these capabilities and provide some general application examples that can be related to the design and manufacture of 3D interconnects.

3D Structuring Capability

Aerosol Jet systems can precisely deposit materials on both planar and non-planar substrates. This is made possible by the relatively high (5mm+) stand-off point of the deposition head and long focal length of the material beam exiting the nozzle. There is no physical contact with the substrate by any portion of the tool (other than the deposition stream), and therefore conformal writing is easily achieved. This allows the process to build 3D conformal features on to shaped components, write into trenches (Figure 3), or over steps and contours (Figure 4).

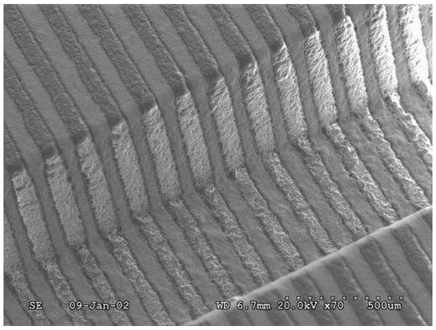

Figure 3. *60µm Ag lines written over a 500µm trench.*

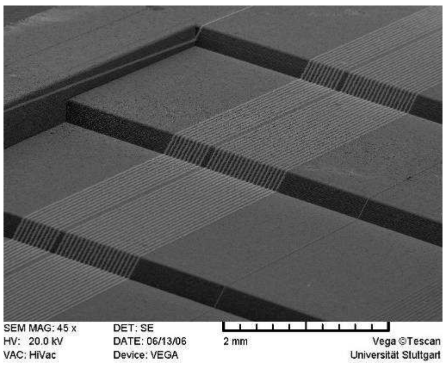

Figure 4. *20 µm Ag lines written over stepped injection molded LCP (Courtesy HSG-IMAT).*

Figure 5 shows an example of conformal packaging in a Smart Card application. This involves 3D direct writing on several different kinds of materials; the interconnect is made from the Cu pad, over the Kapton layer and epoxy adhesive and on to the Si chip. In this case the height difference is approximately 150μm between the Cu pad and the chip. This allows the replacement of the traditional wire bond and reduction of overall part thickness. An additional benefit is improved mechanical reliability as the relatively delicate wire bonds are eliminated. After the Ag interconnects were written the device is processed in an oven at 200°C to sinter the interconnects.

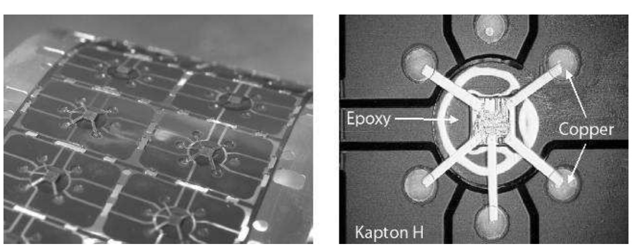

Figure 5. *150µm wide silver interconnect over an epoxy bump and Kapton.*

To meet increasing functionality requirements for SmartPhones, personal entertainment, and other advanced technology devices, 3D Package-on-Package (PoP) interconnects were printed using the Arosol Jet print process. Conductive interconnects, <30 µm wide by <10 µm tall, were printed (Figure 6) from the PCB interface pad onto the sidewalls of vertically staked dies over varying contact layer material (polyimide, Au, Pd, Parylene C, solder mask). Electrical performance (conductivity) of the material was measured at < 5 µ–Ohm*cm when cured at ~200ºC for ~30 minutes. By multiplexing Aerosol Jet print nozzles throughput for printing entire boards of devices was under 1 hour.

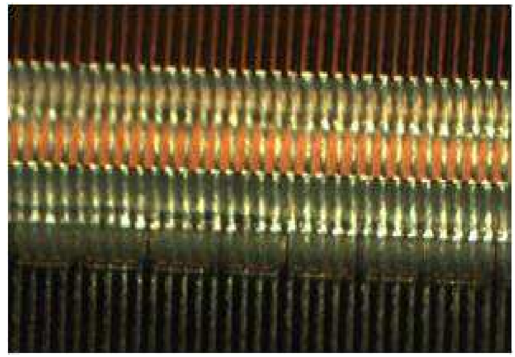

Figure 6*. 3D Silver Interconnects at <30µm wide by <10µ tall with line-to-line spacing of <75µm*

Low Temperature Processing

Once the material has been deposited, conventional approaches for many commercial metal inks require high-temperature treatment often up to 250°C or higher. For non-sensitive polymer substrate materials such as LCP, PA6/6T, re-flow or cure ovens can be used to sinter the deposited material. However, certain substrates tend to have limited temperature capability, for example polycarbonate and polyester, have a temperature limitation of around 100°C. This sensitivity requires a manufacturing process that can deposit and process the material at low temperatures. Aerosol Jet systems can locally process the deposition on substrates, using an integrated laser module that sinters the deposit while leaving the substrate unharmed. The end result is a high-quality thin film with excellent edge definition and near-bulk resistivity, typically 2-3x bulk but dependent on ink type. An example of low temperature processing is shown in Figure 7. This is a low cost polymer display application where temperature sensitive PMMA is used as the substrate to reduce costs. Aerosol Jet was used to write the Ag gates and interconnects which where then laser sintered without damaging the PMMA.

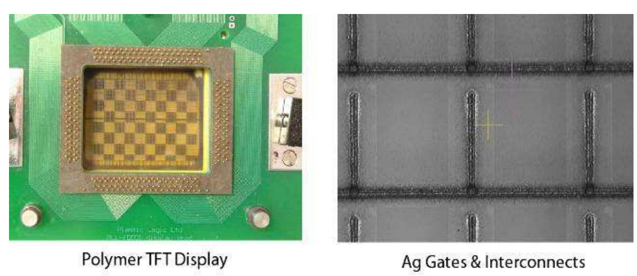

Figure 7. *Low Cost Polymer Display. Laser processed Ag gates and interconnects on PMMA, (Resistivity ~8 µOhm-cm).*

High Quality Deposits

Deposit quality is dependent on the ink type used, the ink-substrate combination and other factors such as substrate roughness. The Aerosol Jet process does not change the chemical or physical properties of the materials deposited or the substrates. In general terms, Aerosol Jet can deposit with:

- Feature sizes down to 10 microns with +/- 10% edge roughness and pitch down to 20 microns
- Good conductivities
- Thickness as low as 100nm or as high as 5 microns (single layer deposit)
- Low surface roughness
- Good adhesion

Aerosol Jet systems reliably produce ultra fine feature circuitry well beyond the capabilities of thick-film and ink-jet processes. Most materials can be written with a resolution of down to 20µm. For Ag, electronic features as small as 10µm with a 20µm pitch can be written.

This capability offers a solution for the production of smaller, high performance components critical to size-sensitive applications like those in the wireless and hand-held device markets where component density is increasing dramatically. The ability of the Aerosol Jet technology to create fine features with complex geometries in 3D from a wide range of materials makes it suitable for the production of both passive and active components, including resistors, inductors, capacitors, filters, micro-antennae, micro-batteries and sensors. The precise edge definition and repeatability of the process are particularly relevant to high frequency requirements. In comparison to screen printing, embedded resistors can be made smaller and more accurately with Aerosol Jet such that no laser-trimming is needed to tune the resistor to the right value.

Gold and Silver inks generally display conductivities approaching bulk properties with conventional sintering and 2-3x bulk with laser sintering. Low viscosity inks can produce mirror-like surfaces while thick film inks have micron scale roughness. Due to the very fine droplet size of the aerosol (typically 1-2µm), even surface profiles in the deposit are common with none of the "coffee staining". Deposit adhesion is highly dependent on ink-substrate combination. For example, gold inks adhere to a wide range of substrates, including glass, ceramics and various polymers. Silver is more sensitive, but also has good adhesion to a wide range of substrates. Typically Aerosol Jet deposits satisfy the standard tape test.

Higher Efficiency Solar Cells

Used in conjunction with Light Induced Plating, the Aerosol Jet process is enabling the industry's first, non-contact fine line printing solution for higher efficiency solar cells. Fine feature collector lines with widths between 18 µm and 60 µm have been produced with the Aerosol Jet process by using new and modified versions of existing screen-printing materials. The narrower, high integrity collector lines have higher conductivity and a lower shadowing effect thereby increasing photovoltaic cell efficiency. Because the process is non-contact, Aerosol Jet systems can print on thinner wafers and with less breakage than screen printing techniques.

Wide Range of Materials & Substrate Combinations

Aerosol Jet systems can deposit a wide variety of materials, including metals, conductors, insulators, ferrites, polymers, adhesives and biological materials. Deposits can be made on virtually any surface material – polymers, silicon, glass, metals and ceramics. This flexibility opens the way for many different 3D Interconnect applications using a single process. The Aerosol Jet process uses a wide range of commercially available inks from many different sources.

Many devices that are manufactured for electronics products require multi-layer manufacturing techniques. The ability of the Aerosol Jet system to deposit conductive, insulating, and adhesive materials layer-by-layer within a single system makes it an attractive solution for the production of embedded passives. A simple 2D example of this multi-layer capability is the deposition of a dielectric and then a Ag layer onto a Cu circuit board pad to create a basic capacitor, Figure. 8. Other examples of multi-layer applications include sub-micron layers for fuel cell applications, high-density interconnect backplanes (organic and metal) for flat panel displays, and micro-sensors for avionics. Other successes with multilayer deposits have been in the biosciences area, such as the generation of bio-sensor structures.

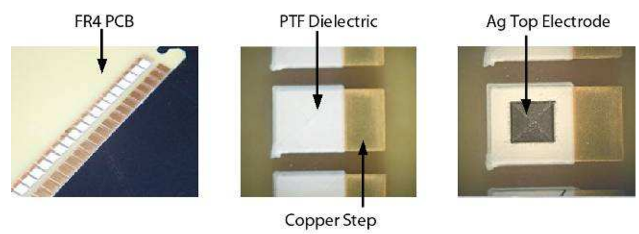

Figure 8. *Multilayer deposition, Polyimide dielectric and Ag deposited onto Cu pads to make a simple capacitor. Capacitance: 19 pF/mm2 @ 15mm Dielectric thickness.*

Environmental Aspects

The Aerosol Jet process works without the need for masks or resists, which results in minimal waste and less environmental impact. As the process writes very finely and precisely, this reduces the amount of material required and waste generated for a given application. If direct metal deposits are used then plating bath is required reducing the quantities of waste material.

Competitive Cost Basis

One of the main drivers for cost reduction using the Aerosol Jet process is the elimination of physical tooling. Aerosol Jet software creates the deposition tool paths direct from standard .DXF CAD data. This digital tooling approach also offers manufacturing agility by allowing designers to quickly and cost effectively test new design alternatives and prototypes. This also offers manufacturing agility which allows designers to quickly and cost-effectively test new prototypes and products. It eliminates the delays and costs associated with tooling sets and other upfront capital required by conventional electronics manufacturing techniques. This feature also makes it much easier to carry out cost effective Rapid Product Development and to validate design changes without the need for "re-tooling". The result is reduced cost and faster time-to-market for new products.

The Aerosol Jet process can reduce the overall number of processing steps, which in turn can help to reduce both capital and operating costs. Since the system can process a wide range of materials and substrates, greater utilization of the capital equipment can be obtained. Process costs in terms of operator input, supplier chain complexity and work flows are reduced.

Material efficiency can often play a key role in reducing the cost of manufacturing operations. The tiny droplets dispensed by Aerosol Jet allow for very thin coatings which also allow for good interaction between differently applied layers. These same femto-liter sized droplets allow for very careful control of dosages dispensed. Since many electronics materials are expensive, their technology is a key enabler for reducing the cost of each device by reducing materials use and waste.

Figure 9. *Demonstrator test pattern (Cu plated on PI) created by the catalyst-layer approach.*

Another alternative for reducing processing steps and cost, compared to traditional mask-etch techniques, is the catalyst-layer approach for producing interconnects or other features. Aerosol Jet systems can directly deposit an activator/catalyst solution in the exact pattern required. The process is then completed by curing at 80^{o}C, and then followed by a standard electroless Cu plating step (Figure 9).

In this sample, the catalyst test pattern has been printed onto a polyimide film and conventional electroless plating for two hours has been used to plate approximately10mm thick Cu onto the pattern. The traces in Figure 10 are 50 mm long and range in width from 10mm down to 500mm. Gap spacing ranges from 1.8 mm down to 300mm. All traces are highly adherent to the substrate and pass the standard tape test. Deposit conductivity is near bulk and similar to standard electroless Cu deposits. The process has also been demonstrated on polymer matrix composites and PET. This technique can be used to reduce cost, especially in patterns requiring combined fine and large area deposits.

PROCESS SCALABILITY

The current Aerosol Jet 300 system is aimed at low volume manufacturing and rapid prototype product development. The system is equipped with a single deposition head and a single deposition nozzle. It can write at speeds up to 200m/s with a high level (5mm) of dynamic accuracy. As higher volume applications are developed, there is a need to scale up the speed of Aerosol Jet manufacturing. Aerosol Jet systems are involved with ongoing projects in scaling atomizer throughput, development of multiple nozzle deposition heads, and closed loop control of the deposition process. These developments are being driven by high volume (millions of parts p.a.) production applications which will be released in 2007 as a replacement to screen printing. These applications are 2D, but the developments will provide the foundation for extension into high volume 3D applications as they evolve.

CONCLUSIONS

This paper has introduced the novel Aerosol Jet deposition process and outlined its features, benefits, and some select application areas. This CAD driven, direct write process is currently being used in a wide range of 2D electronics applications. However, the process also has the capability to write conformally, providing an enabling technology for 3D production. Designers of 3D interconnects can now harness the unique features of Aerosol Jet systems to create designs which offer a wide range of time, cost and quality benefits. Since many MID applications are evolving, Aerosol Jet can also be a powerful, flexible product development tool, as well as a viable production solution.

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